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Disruption rates for one vulnerable soil in Organ Pipe Cactus National Monument, Arizona, USA

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ABSTRACT

Rates of soil disruption from hikers and vehicle traffic are poorly known, particularly for arid landscapes. We conducted an experiment in Organ Pipe Cactus National Monument (ORPI) in western Arizona, USA, on an air-dry very fine sandy loam that is considered to be vulnerable to disruption. We created variable-pass tracks using hikers, an all-terrain vehicle (ATV), and a four-wheel drive vehicle (4WD) and measured changes in cross-track topography, penetration depth, and bulk density. Hikers (one pass = 5 hikers) increased bulk density and altered penetration depth but caused minimal surface disruption up to 100 passes; a minimum of 10 passes were required to overcome surface strength of this dry soil. Both ATV and 4WD traffic significantly disrupted the soil with one pass, creating deep ruts with increasing passes that rendered the 4WD trail impassable after 20 passes. Despite considerable soil loosening (dilation), bulk density increased in the vehicle trails, and lateral displacement created berms of loosened soil. This soil type, when dry, can sustain up to 10 passes of hikers but only one vehicle pass before significant soil disruption occurs; greater disruption is expected when soils are wet. Bulk density increased logarithmically with applied pressure from hikers, ATV, and 4WD.

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1. Introduction

Land uses in the North American deserts that cause soil disruption are widespread and increasing on public lands (Belnap, 1995; Leu et al., 2008), with long lasting effects particularly in the form of tracks (Vogel and Hughson, 2009) and illegal trails (Cabeza Prieta NWR, 2011). An understanding of the rates of surface disruption and soil compaction is a vital component of management plans created to minimize the adverse effects of these uses (e.g., off-road races in arid landscapes). Compaction and its effects on soil properties are widely recognized in agricultural and engineering practices (Karafiath and Nowatzki, 1978), as well as for a variety of land uses (Lovich and Bainbridge, 1999), including off-road vehicles (Webb, 1982, 1983; Wilshire and Nakata, 1976), livestock grazing (Brooks et al., 2006), and human trampling (Liddle and Grieg-Smith, 1975; Weaver and Dale, 1978). Military exercises involving extensive vehicle use, in particular, cause substantial soil compaction and surface disruption (Krzysik, 1985; Prose and Wilshire, 2000).

Rates of soil disruption are not well known for most land uses, although some studies have measured the rates of compaction from hikers (trampling) and off-road vehicle (ORV) use (Liddle and Grieg-Smith, 1975; Weaver and Dale, 1978; Webb, 1982), usually at one moisture content for one soil. ORVs cause significant compaction with as few as 1–10 passes (Davidson and Fox, 1974; Vollmer et al., 1976; Wilshire and Nakata, 1976). Webb (1982, 1983) reported that soil density increases logarithmically with increasing numbers of passes, asymptotically approaching a maximum level. Prose and Wilshire (2000) reported that compaction under conventional recreational vehicles may be greater than under tracked vehicles, such as tanks, owing to the higher ground pressures under conventional tires.

Soil compaction may retard the establishment of desert plants (Adams et al., 1982; Prose and Wilshire, 2000; Prose et al., 1987), but low levels of compaction may benefit annual plant growth because of increases in water-holding capacity (Brown and Schoknecht, 2001; Lathrop and Rowlands, 1983). Compaction of soils is a major factor contributing to decreased infiltration rates, increased runoff, and accelerated soil erosion (Iverson, 1980; Iverson et al., 1981; Snyder et al., 1976). Roads are a major source of fugitive dust (Campbell, 1972; Goossens and Buck, 2009, 2011), and water erosion can be 10–20 times higher on slopes (Iverson, 1980;

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Iverson et al., 1981). Reductions in infiltration rates are often ascribed to decreases in total soil porosity (Eckert et al., 1979), and the magnitude of the decrease has been shown to depend upon the soil moisture content, texture, and the compacting load (Webb, 1983).

Few researchers have attempted to quantify changes in soil properties as functions of the intensity of use (Liddle and Grieg-Smith, 1975; Webb, 1982), although vulnerability of soils to compaction is generally the inverse of what is known from engineering studies, where the objective is to determine the types of soil that will compact the most for roadbeds or other engineered fills (Webb, 1983). The increase in soil density after desert surface 'loading' is commonly greatest a short depth below the surface instead of actually at the surface (Arndt, 1966; Parker and Jenny, 1945), but density changes have been measured to depths down to one meter (Prose and Wilshire, 2000; Snyder et al., 1976). Most of these effects can be explained from knowledge of the mechanics of soils, and some effects, including density changes with increasing numbers of vehicle passages, can be partially predicted.

1.1. Processes of soil compaction

By definition, compaction results from the application of normal stress, also known as applied pressure, to a soil surface, resulting in a decrease in pore volume and an increase in bulk density (Johnson and Sallberg, 1960). Soil strength generally increases in compacted soils as well, and the decrease in pore volume alone results in surface lowering in tracks. Hikers and vehicles create a complex, three-dimensional stress field while passing over soil, including in a normal (vertical) stress that compacts soil and shear stresses that cause dilation, or soil loosening with reduced density (Webb, 1982). Depending upon the magnitude of the normal stress, compaction typically occurs between 0.05 and 0.30 m depth, with dilation occurring at very shallow depths. Most heavily-used dirt roads have a thin, loose layer of soil over a densely compacted layer, which complicates compaction measurements. Commonly used laboratory tests apply normal stresses while minimizing shear stresses, which can create problems when comparing field and laboratory measurements.

1.2. Vulnerability of soils to compaction

The amount of compaction that a soil can sustain is a function of particle-size distribution, structure, and water content at the time of compaction (Bodman and Constantin, 1965; Williams and MacLean, 1950). Poorly sorted soils, such as loamy sands and sandy loams, compact more readily than well-sorted soils, such as eolian sand or playa surfaces (Webb, 1983). Gravel may increase compaction over what would occur with the <2 mm fraction alone (Webb, 1983); although large amounts of gravel may inhibit compaction, as particle-to-particle contacts in gravel may resist stress that might otherwise decrease soil unit volume. Therefore, empirical judgments can be used to assess general soil vulnerability to compaction.

Soils compact the most when stresses are applied at water contents slightly less than field capacity, which is the water content that a saturated soil drains to after about 24 h (Webb, 2002). At water contents approaching zero, pore-water pressures are high, increasing the resistance to applied pressure (Greacen, 1960), whereas at water contents near saturation, volume decreases can only be attained by forcing water from the soil, and drainage rates become the limiting factor. Laboratory measurements indicate that soils vulnerable to compaction have a sigmoidal relation between water content and density, with a minimum at low moisture content and a maximum at near field capacity.

2. Background and setting

Organ Pipe Cactus National Monument (ORPI) is a unit of the National Park Service on the US – Mexico border in southwestern Arizona (Fig. 1). Established in 1933, this park contains 133,800 ha of Sonoran Desert landscape as well as having a 47.9 km boundary with Mexico (Fig. 1). ORPI also shares boundaries with Cabeza Prieta National Wildlife Refuge (Cabeza Prieta NWR) on the west, the Tohono O'odham Reservation on the east, and a combination of Bureau of Land Management and private lands on the north. ORPI is affected by a number of compaction-causing uses, including hikers and off-road vehicle use.

As part of its border security operations, the U.S. Customs and Border Protection (CBP) built a Forward Operating Base (FOB) on the western border between ORPI and Cabeza Prieta NWR at 32.13097° N, 113.08527°W, and 337 m elevation (Fig. 1). On 5–6 August 2010, prior to construction, we conducted experimental studies at the FOB site. The vegetation was mainly *Larrea tridentata* (creosotebush) at less than 5% cover with scattered *Ambrosia chenopodifolia* and other annual and perennial species.

2.1. Climate

The climate in the western part of ORPI, recorded from October 1987 to December 2011, is arid with average July high temperatures of 39.4 °C, an average low December temperature of 4.76 °C, and a mean annual precipitation of 205 mm. Rainfall in August 1988 was 375 mm at this station, resulting from Tropical Cyclone John. After removing this anomalous month from the precipitation record, the mean annual precipitation is 183 mm. Approximately half of the precipitation occurs from June through September as monsoonal thunderstorms, and August is the month of highest precipitation.

2.2. Soil

The soils on the alluvial plains on the northwestern part of ORPI are mostly the Growler–Anthro Complex (Soil Conservation Service, 1972), which occupies 5836 ha or 4.4% of the park unit. The soil type at the FOB site is Gilman very fine sandy loam, a soil that comprises about 10% of the Growler–Anthro complex and is mapped individually as another 10,676 ha for a total of 11,300 ha (8% of ORPI). Prior to our experimental work, the soil at the FOB site appeared to be undisturbed with no visible signs of soil disruption or previous compaction. Using a combination of sieve and hydrometer analyses, the Gilman very fine sandy loam had a gravel (2–4 mm D_{50}) content of 4.1%, a sand (0.63–2 mm D_{50}) content of 90.0%, a silt (0.002–0.063 mm D_{50}) content of 3.7%, and a clay (<0.002 mm D_{50}) content of 2.3%. The Folk sorting coefficient (Folk, 1974) of 2.16 indicates a poorly sorted soil, indicating that this soil likely is vulnerable to soil compaction. The moisture content at the time of the experiment was a very low 1%, indicating air-dry soil and providing conditions for least amount of soil disruption.

The soil profile included a 2 cm thick A1 horizon of platy silty soil with weak vesicular development, underlain by a 20 cm thick, tan-colored A2 horizon, which had the texture of a sandy loam. Underneath the A2 horizon, a Bt horizon consisted of 10 cm of an incipient argillic (clay-enriched) horizon, which was underlain by Stage 1 carbonate in a reddish Bk horizon. Because of its sandy loam texture, the Gilman very fine sandy loam is considered to be highly vulnerable to soil compaction. Of the 133,800 ha of ORPI, soils considered to be highly vulnerable to compaction occur in 46,700 ha (35%, Fig. 1).

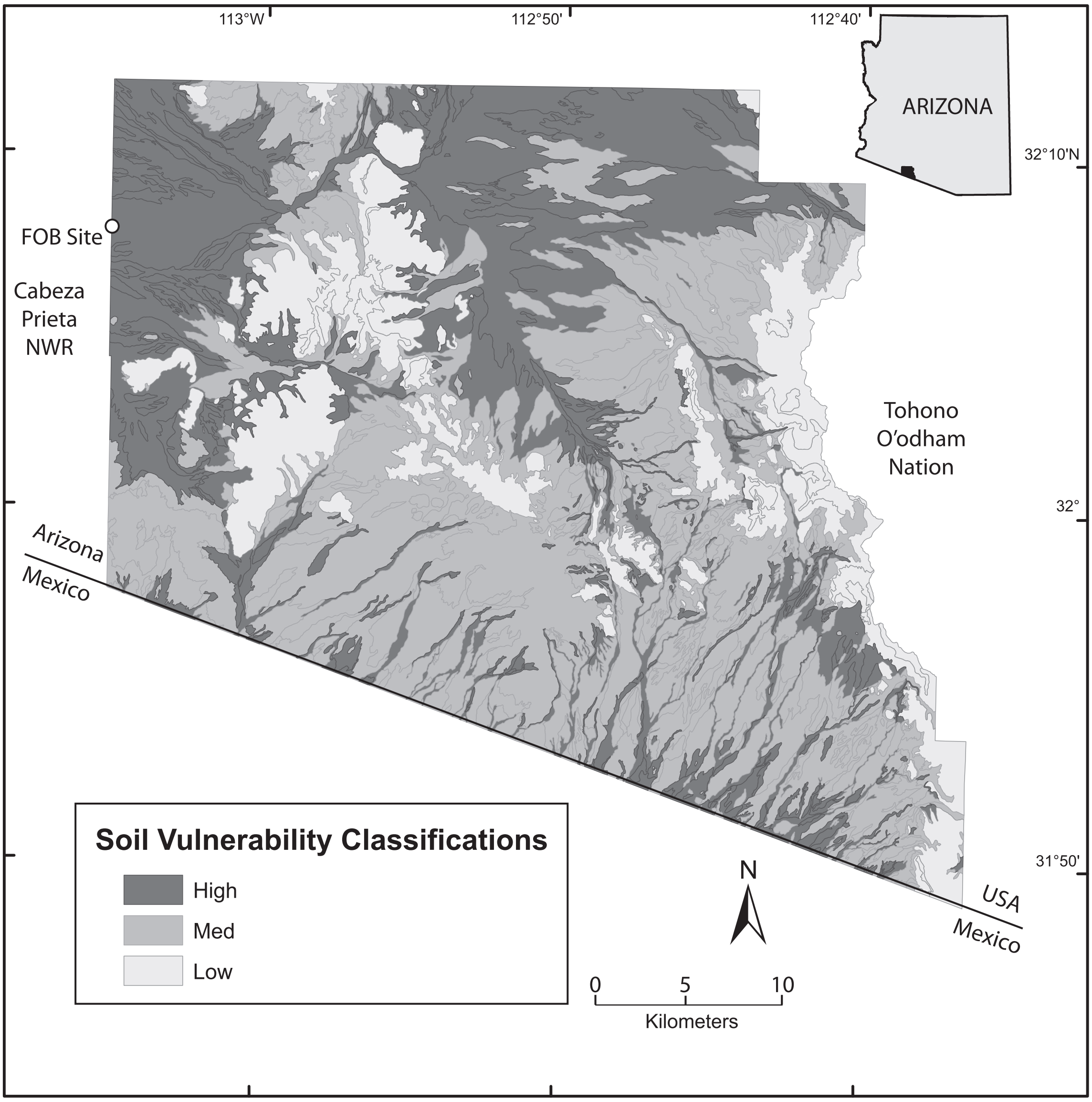

Fig. 1. Map of Organ Pipe Cactus National Monument, southwestern Arizona, showing the spatial distribution of soils by vulnerability classes. Distribution of soils is from Soil Conservation Service (1972), and vulnerability assessments are based on laboratory compaction analyses and particle-sorting characteristics (Webb et al., 2013).

3. Methods

3.1. Experimental design

Table 1 provides a framework for the experimental design with the number of replicate measurements made within each treatment type. Within an area of approximately 1 ha, we created a control area and a system of 16 trails using treatments of foot traffic, an all-terrain vehicle (ATV), and a four-wheel-drive truck (4WD). These trails were straight and approximately 50 m long (Fig. 2). Table 2 shows the number of passes and applied surface pressure for each type of treatment. For foot traffic, we considered one pass to be five hikers walking in a line for most of the treatments except 100 passes, for which we used four different and fresh hikers with a higher applied surface pressure per pass (Table 2). We used the weight of each hiker and their shoe size to calculate the applied surface pressure per individual, then summed the applied pressure per pass for the hikers involved in the experiment. Hikers do not walk in each other's footsteps and therefore a correction factor must be applied to reduce applied pressure per pass. For one pass, hikers impacted 87.5% of the distance along a trail approximately 10 cm wide; thus, we reduced the applied pressure by 12.5% in our summary calculations (Table 2).

The ATV and 4WD weights were obtained using commercial scales, and the contact area of each tire was measured in the field at the tire pressure that was used. The vehicles were operated at a constant, relatively low velocity ($\sim$ 20 km/h) for the straight-line segments, reducing shear associated with turns or acceleration/deceleration and minimizing vertical bounce that would create spikes in locally applied pressure. The ATV was used for a maximum of 136 passes without bogging down in the loosened soil; in contrast, the 4WD treatment was stopped at 20 passes because the rear differential began dragging on the surface between the tire tracks and the tires began to spin, creating significant shearing of soil in the tracks (Fig. 2). This shearing created unexpected changes in soil strength and bulk density.

3.2. Field measurements

After all foot and vehicle trails were established, we made three types of measurements of surface disturbance and soil compaction.

Table 1
Experimental design for the forward operating base (FOB) experiment at Organ Pipe Cactus National Monument, Arizona, USA.

Treatment type	Track number	Number of passes (n)	Topography measurements	Penetrometer measurements	Bulk density measurements
Undisturbed	1	0	3	25	10
Foot traffic[a]	1	1	3	25	10
	2	5	3	25	10
	3	10	3	25	10
	4	50	3	25	6
	5	100	3	25	6
All-terrain vehicle (ATV)	1	1	3	25	6
	2	5	3	25	6
	3	10	3	25	6
	4	20	3	25	6
	5	100	3	25	6
	6	136	3	25	6
Four-wheel drive vehicle (4WD)	1	1	3	25	6
	2	5	3	25	12
	3	10	3	25	12
	4	14	3	25	12
	5	20	3	25	12

[a] Hikers are either 4 or 5 hikers in a line; see Table 2.

For each treatment (Table 2), we measured surface topography across each of the 16 trails (Table 1) at 3 randomly selected sites. Using a level line perpendicular to the trail and held in place by two portable stands, we measured the distance down from this line at inflection points selected to measure change in surface elevation, in the dilation zone, at the margins of tracks, and in the maximum depth of ruts. Seven points were used for hiker tracks and 9 points for vehicular tracks (Fig. 2C). Changes in surface topography were determined by summing the absolute values of deviations from a level surface, including negative depressions associated with compacted soil and positive berms created by lateral dilation along the sides of trails. An example of surface topography measurements is given in Fig. 3.

Penetration depth is an index measurement of soil compaction that is least sensitive to gravel content but most sensitive to moisture content (Webb, 1983, 2002). We used a Jornada impact penetrometer (Herrick and Jones, 2002) to measure 25 penetration depths in each treatment (Table 1). Penetration depth, a common index of soil compaction that is inversely related to soil strength, is the depth to which an operator can drive a 30°, 920 mm^2 cone into the soil using 25 drops of a 2 kg weight from a height of 20 cm. The normal force exerted on the penetrometer at insertion beyond the cone is 3.92 J/drop for a total cumulative force of 98 J. For each treatment, we made 25 replicates of penetration depth.

Bulk density is a fundamental soil property unrelated to moisture content. We measured bulk density in the 0–60 mm depth using a coring device 57 mm in diameter that was designed to collect intact samples. We collected 6–12 samples from each treatment (Table 1). To obtain moisture content, the recovered soil was dried in a drying oven at about 60 °C for 48 h; the lower temperatures were used to minimize baking and loss of structural water from clay minerals. The results were expressed as a dry-weight bulk density (kg/m^3). At each site, 6–10 bulk density samples were collected from each treatment type (Table 1).

3.3. Laboratory measurements

Proctor compaction analyses provide data on maximum soil density achieved over a range of moisture contents (Bradford and Gupta, 1986). In general, Proctor compaction curves rise from a minimum bulk density at a low moisture content (~1–2%) to a high bulk density at a moisture content generally considered to be at or near field capacity. A 20 kg soil sample was collected from 0 to 6 cm depth at the FOB site for laboratory measurements of compactability. Proctor compaction curves were run on each sample using the standard method as specified in the ASTM standards (ASTM D 698-00a, D 2168–02a). A total of 7 water contents, ranging from 0 to 16% by weight, were measured using a standard mold and 3 lifts with 25 blows per lift from a PLOOG Engineering automated soil compactor.

After each Proctor test, we used a U.S. Army Corps of Engineers (COE) cone penetrometer (Bradford, 1986), model H-4120, to measure penetration resistance on the compacted soil samples still in the Proctor molds. This hand-held penetrometer measures only the pressure required to push the cone 25.41 mm into the compacted soil at a constant rate of 3 cm/s. A proving-ring gauge is read for pressure when base of cone is flush with surface of the soil (Bradford, 1986). A total of 4 measurements were made for each water content – maximum bulk density.

3.4. Data analyses

Data was statistically analyzed using Systat 10.1 (Systat Inc., 2002). In particular, we used a log-linear regression to evaluate the change in a variable with increasing numbers of passes or applied surface pressure and a standard ANOVA test to evaluate change in variance between treatments. We used the commonly accepted standard of probability of occurrence less than 0.05 (probability $p < 0.05$) to determine differences among variables tested.

4. Results and discussion

4.1. Surface topography

Measurements of cross-trail topography show that the magnitude of change increases differed among treatment types (Fig. 4). There was a significant log-linear increase in the amount of change in surface topography with the number of passes for foot traffic ($p = 0.04$). These data indicate that foot traffic creates only slight depressions <0.5 cm depth that are likely only detectable after 10 passes (50 hikers). ATV passes also increased surface topography above the undisturbed level, starting with 10 passes, with a log-linear increase in topography thereafter ($p < 0.0001$). ATV depressions exceed 1 cm between 10 and 20 passes and are greater than 4 cm after 100 passes (Fig. 4B).

The 4WD trails increased variance in the surface topography significantly ($p < 0.001$), but had peak variance after only 5 passes. However, increasing passes progressively created deeper ruts as well as increasingly larger dilation berms on the margins and between the ruts (Fig. 3), and the change in average deviation

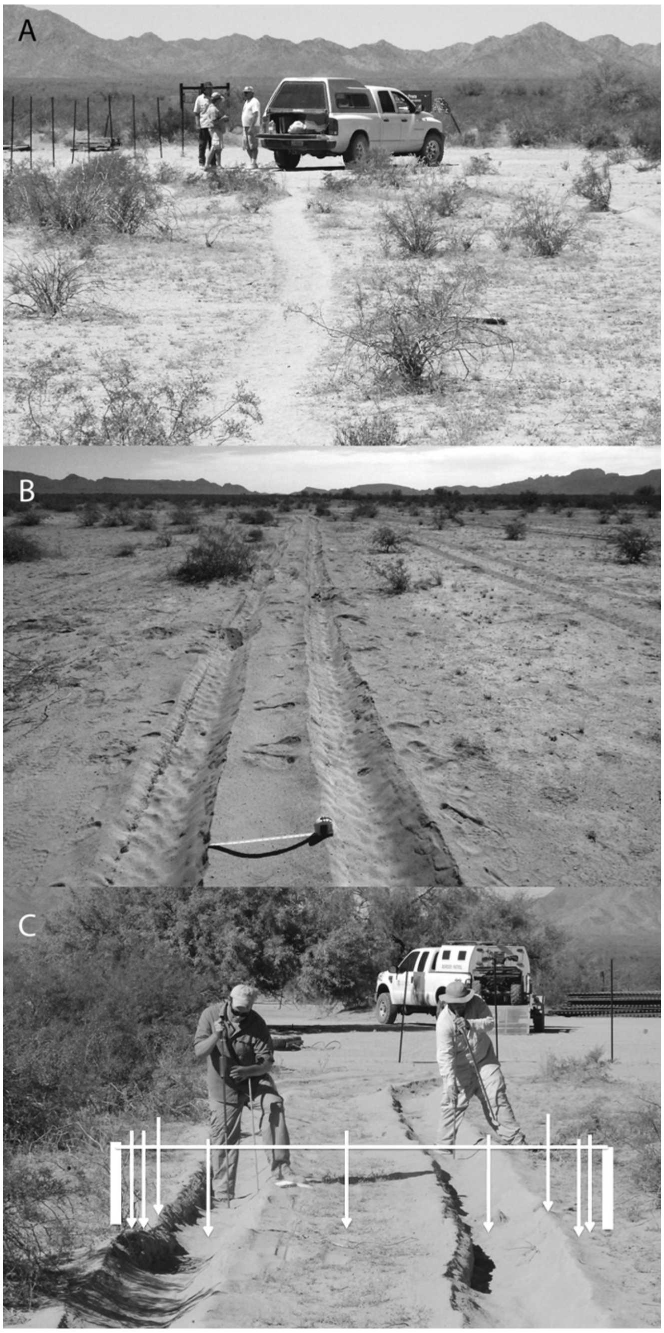

Fig. 2. Maximum pass effects on a desert soil at Organ Pipe Cactus National Monument. A. 100 hiker passes. B. 136 ATV passes. C. 20 truck passes with a schematic diagram showing topographic measurements.

Table 2
Ground pressures for hikers, all-terrain vehicle (ATV), and four-wheel drive (4WD) vehicle used in the forward operating base (FOB) experiment at Organ Pipe Cactus National Monument, Arizona, USA.

Treatment type	Passes (n)	Weight (kg)	Surface area (m^2)	Applied pressure, nP (kN/m^2)
Foot (5 hikers in line)[a]	1	310	1.36	2.24
	5	310	1.36	11.2
	10	310	1.36	22.4
	50	310	1.36	112
Foot (4 hikers in line)[b]	100	379	1.49	249
All-terrain vehicle (ATV)	1	419	0.85	4.83
	5	419	0.85	24.2
	10	419	0.85	48.3
	20	419	0.85	96.7
	100	419	0.85	483
	136	419	0.85	657
Four-wheel drive vehicle (4WD)	1	3393	1.09	30.5
	5	3393	1.09	153
	10	3393	1.09	305
	14	3393	1.09	427
	20	3393	1.09	611

[a] Five hikers in a line (applied pressure per pass = 2.24 kN/m^2) affect 87.5% of the distance traversed.
[b] Four hikers in a line were used with higher applied pressure per pass (2.24 versus 2.49 kN/m^2).

decreased, likely as a result of soil collapse into the ruts (Fig. 4C). The trail edges are dilated with loose, low-density soil, whereas trail centers have a 2–4 cm layer of loose material caused by tire shearing underlain with compacted soil. Shearing displaced soil from the center of the rut to the margin, increasing the rut depth to greater than would be expected from compaction alone. Our experiments show that 20 passes creates ruts up to 10 cm deep in this dry soil (Fig. 3E).

4.2. Soil penetration depth

Penetration depth measurements were unusual and unexpected for this dry soil, and our results appear to reflect the decrease in soil strength caused by shearing in addition to the lack of sensitivity in the soil sampler to thin compacted zones beneath the tracks. For foot traffic (Fig. 5A), penetration depth remained constant up to 10 hiker passes; for 50–100 passes, penetration depth increased, indicating a lowering of soil strength. For ATV traffic, penetration depth decreased from 10 to 100 passes, which is the expected result from a compacting force; at 136 passes, however, the penetration depth was the same as the undisturbed soil (Fig. 5B). For 4WD traffic, penetration depth increased except for 14 passes (Fig. 5C). Typical penetration depths were 20–30 cm (Fig. 5).

The Jornada impact penetrometer is designed to average resistance to penetration over its depth range. As a result, it integrates the surficial low-strength dilation zone with a higher strength compaction zone and unaffected subsurface soil, which creates problems with interpreting measurements of rates of compaction in a dry soil. The zone of maximum compaction in most soils is 5–10 cm depth (Webb, 1983), and standard operation of the Jornada impact penetrometer integrated soil strength over more than twice that depth. Applied surface pressure and shearing disintegrated the vesicular structure of the surficial horizon, leading to lower soil strength in this dry soil. We anticipate that, if measurements were made on wet soil, the penetration depth results would have shown an increased soil strength, as has been found in other studies (Webb, 1982).

4.3. Bulk density

In general, bulk density measurements yielded responses that would be expected from other studies with the exception of some changes apparently related to shearing of the dry soil. Undisturbed bulk density for the Gilman very fine sandy loam was 1490 ± 40 kg/m^3, which is a typical density for an undisturbed soil with this texture. A total of 5 passes by hikers was required to increase bulk density significantly (1660 ± 70 kg/m^3) above the undisturbed value (Fig. 6A). One pass by the ATV and 4WD caused significant increases in bulk density to 1720 ± 60 and 1690 ± 40 kg/m^3, respectively (Fig. 6B, C). Bulk density generally increased with increasing passes by hikers, but both ATV and 4WD traffic generally resulted in a high bulk density after the first pass, and thereafter little statistically significant changes occurred with increasing number of passes (Fig. 6). The greatest changes occurred with the initial pass and probably resulted from the collapse of vesicles (macropores) in the surface horizon. Particularly for the 4WD treatment, the lack of change from 1 to 20 passes likely resulted from the loosened, sheared soil overlying compacted soil. Because the core sampler sampled in the 0–6 cm depth, the loosened and compacted soil layers were averaged.

All three treatments involved applied ground pressure, and following previous studies (Webb, 1983), we calculated the number of passes times the applied ground pressure per pass (nP, Table 2). Combining all treatments, a regression analysis yields a significant relation between dry-weight bulk density (kg/m^3), BD, and nP (kN/m^2) as:

$$BD = 1,576 + 69.0 \cdot \log(nP), \quad r^2 = 0.66 \tag{1}$$

This relation shows that compaction is highly variable with low nP (see hikers, ATV traffic ~50 kN/m^2, Fig. 7). Because hikers do not impact 100% of the ground area in their trails, even with 5 hikers in a line, this result is expected; the increase in bulk density for one ATV pass was unexpected. At high levels of nP, the effect of shearing and soil dilation for the 4WD tracks contrasts with the hiker and ATV results (nP > 300 kN/m^2, Fig. 7).

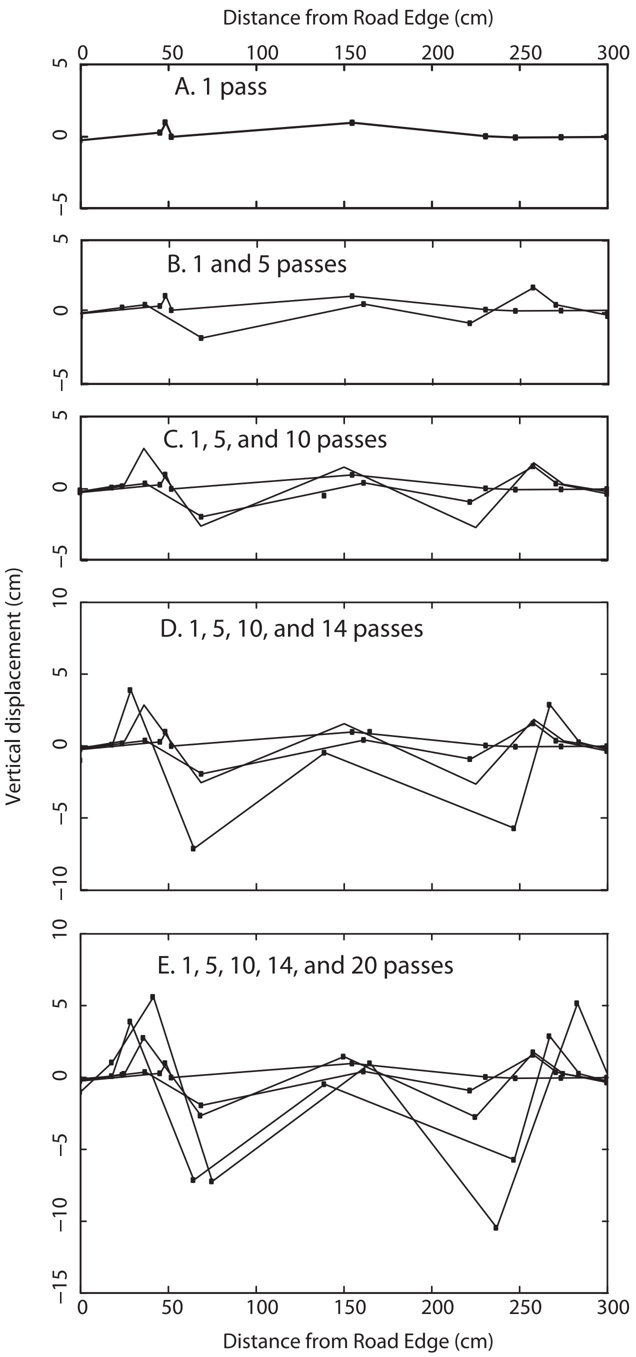

Fig. 3. Sequential changes in surficial topography with increasing numbers of truck passes.

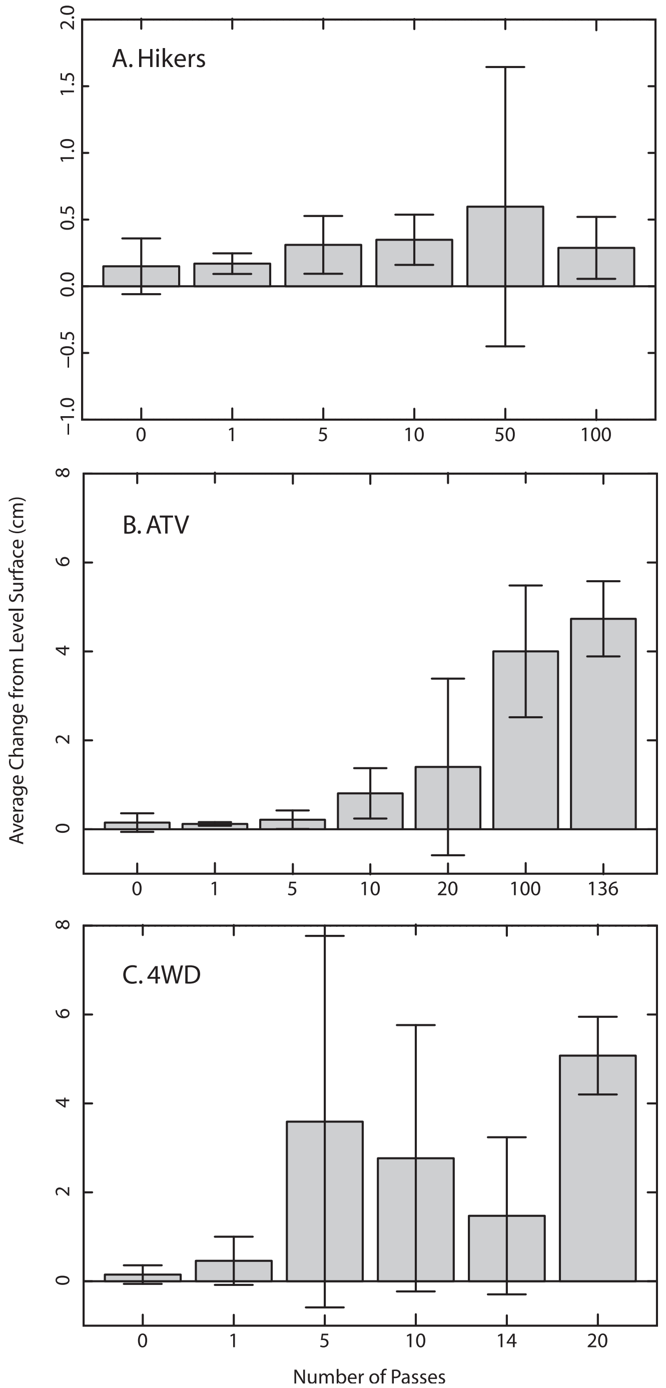

Fig. 4. Average change in the absolute value of deviations from a horizontal straight line across trails ($n = 3$) with increasing numbers of passes. A. Foot traffic. B. ATV traffic. C. Truck traffic. Error bars = ±1 SD.

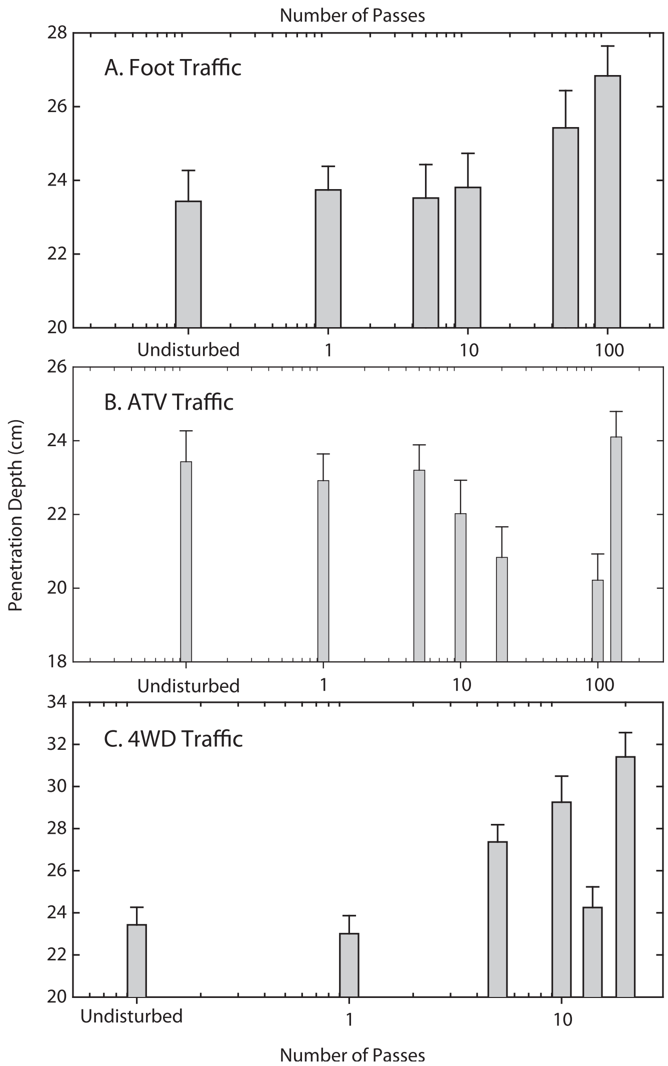

Fig. 5. Changes in penetration depth with increasing passes. A. Hiker traffic. B. ATV traffic. C. 4WD traffic.

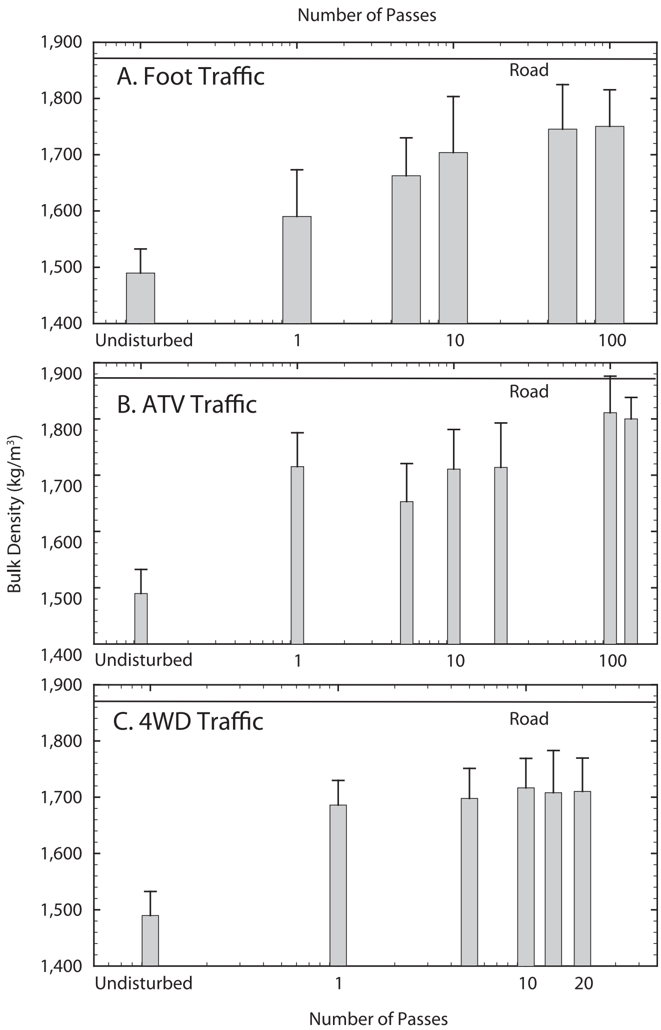

Fig. 6. Changes in bulk density with increasing passes. A. Hiker traffic. B. ATV traffic. C. 4WD traffic.

4.4. Proctor compaction and penetration resistance tests

The Proctor analyses (Fig. 8A) underscore the vulnerability of the Gilman very fine sandy loam to soil compaction. This graph represents a typical desert soil in that maximum bulk density increases as water content goes to zero, which is the compaction behavior of most desert soils. This soil is compacted to its highest bulk density at a water content of 8.5%, when a maximum bulk density of 1912 kg/m^3 was achieved (Fig. 8A). Above this water content, maximum bulk density decreases owing to interference from water in soil pores. The highest bulk density achieved in the Proctor test was greater than the bulk density of a road at the FOB site (1870 kg/m^3, Fig. 9), which again had a thin dilation zone at its surface. The difference in maximum bulk density between dry and wet conditions in the Proctor test is about 200 kg/m^3, which is indicative of the vulnerable nature of this soil to surface disturbance.

The Proctor results help to place the field measurements of bulk density into perspective (Fig. 9). Maximum soil compaction at all moisture contents is at least 267 kg/m^3 higher than the undisturbed bulk density; the increase at 8.5% moisture content is 424 kg/m^3. The differences in maximum bulk density between dry and wet conditions and the difference between undisturbed and maximum bulk densities show the highly vulnerable nature of this soil to surface disturbance. Our maximum number of passes for all treatments was lower than the maximum bulk density expected for 1% moisture content, indicating that more passes would be required at that moisture content to achieve maximum potential bulk density.

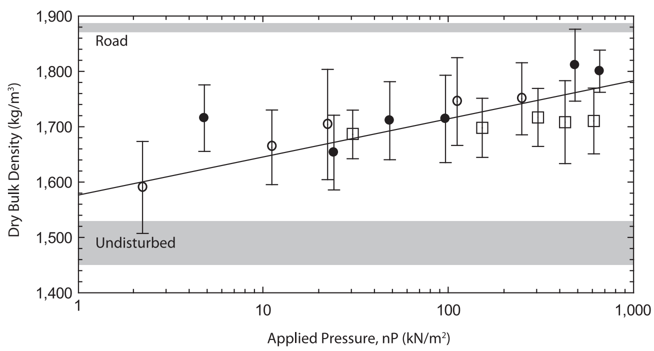

Fig. 7. Applied pressure (nP) versus bulk density data from the FOB site at Organ Pipe Cactus NM, Arizona. Open circles = hikers, closed circles = ATV traffic, open squares = 4WD traffic, and error bars and the bands for road and undisturbed indicate ±1 SD. The line is a regression fit with $r^2 = 0.66$ (see Equation (1)).

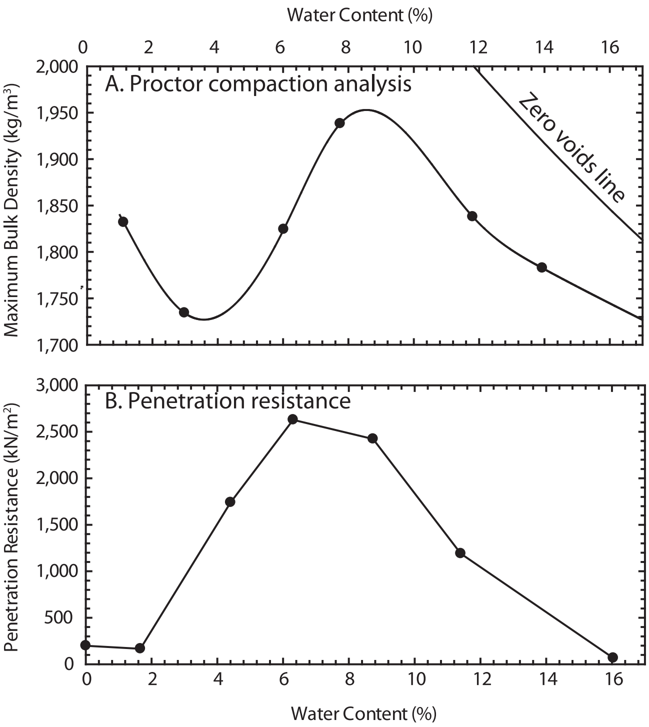

Fig. 8. A. Proctor compaction curve for the Growler–Anthro Complex soil at the forward operating base (FOB) site. B. Penetration resistance on the Proctor maximum compaction samples.

Penetration resistance measurements (Fig. 8B), made with the COE penetrometer, yielded a striking result that also underscores the highly vulnerable nature of the Gilman very fine sandy loam to surface disturbance. At 1% moisture content, the same as the field moisture content, penetration resistance is low, showing that this soil has decreased soil strength when nearly dry, even at its maximum compaction level. The highest penetration resistance occurred at 6% moisture content, which corresponds to a maximum bulk density only slightly higher than the lowest density measured in drier soil. The COE penetrometer results help to explain our field measurements and place them into perspective in the overall compaction vulnerability over the expected range in moisture contents. When dry, the Gilman very fine sandy loam compacts as a result of collapse of vesicles and other macropores but decreases in soil strength, probably as a combination of decreased soil-water capillary forces as well as a collapse of soil aggregates in the surficial A1 horizon.

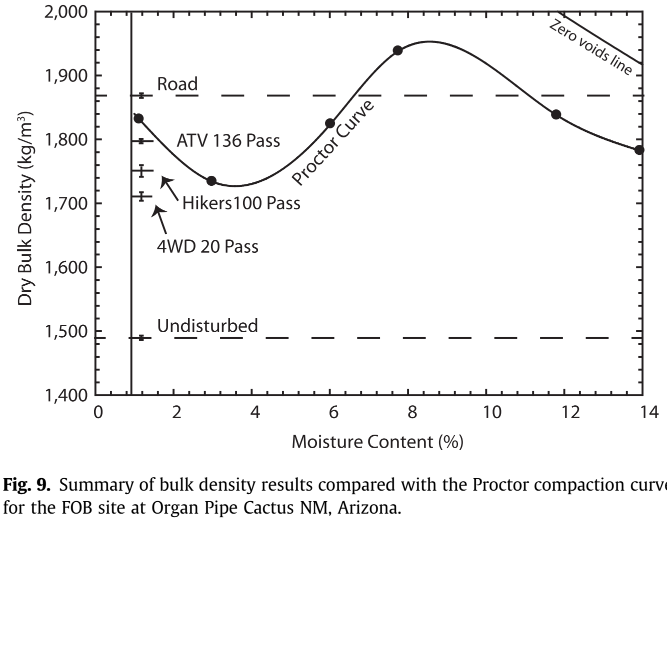

Fig. 9. Summary of bulk density results compared with the Proctor compaction curve for the FOB site at Organ Pipe Cactus NM, Arizona.

5. Conclusions

We measured significant soil disruption and compaction from hikers and vehicle traffic for one soil at Organ Pipe Cactus National Monument (ORPI) in western Arizona, USA. At the time of our measurements, this soil, a Gilman very fine sandy loam, was air dry, allowing us to measure a vulnerable soil at a low resistance to soil compaction. We created straight-line trails for hikers (one pass = 4–5 hikers in a line), an all-terrain vehicle (ATV), and a four-wheel drive truck (4WD). The effects of hikers were significant at ≥10 passes, with changes in surface topography, penetration depth, and bulk density. The effects of ATV and 4WD traffic were measurable after one pass and were substantial for ≥10 passes. The combination of field and laboratory measurements, including Proctor analyses, support the qualitative contention that this soil is vulnerable to soil compaction.

Quantification of the rates of soil compaction in desert soils is difficult owing to numerous complicating factors and the spatial variability of desert soil properties, particularly surficial particle-size distributions. It is extremely difficult to capture the different types of applied surficial stresses that can result from vehicle operations, particularly when rates of speed, acceleration/deceleration, and especially vehicle turning is considered. We operated vehicles at a constant, safe speed to create our treatments, and it is difficult to assess how representative this is of vehicle usage in deserts. Although only one soil type at one moisture content was measured, we used the Proctor compaction test to place a more general context on the compaction vulnerability of desert soils. Although the Gilman very fine sandy loam has properties similar to many desert soils worldwide, spatial variability of desert soil physical properties is extremely high, and most desert soils are more poorly sorted with higher gravel contents than the soil we chose for our experiments. Proctor compaction tests provide one method for comparing the compaction properties of diverse desert soils (Webb et al., 2013).

Perhaps the largest problem with quantifying rates of soil compaction in desert soils concerns the fact that, in general, soil compaction occurs over a range of soil moisture contents instead of at just one moisture content, as we had in our experiment. If passes occur weeks or months apart, then the compaction characteristics of the soil change and the rate of soil compaction, as reflected in bulk density (Fig. 7), is likely to change significantly. Furthermore, applied surface pressure, particularly when shearing associated with acceleration/deceleration occurs, can create a soil dilation zone over compacted soil, leading to the confounding effect of soil in roads with lower bulk density than the maximum attained in laboratory tests (Fig. 9).

Few previous studies have assessed rates of soil disruption and compaction in dry soils that are vulnerable to soil compaction. We measured some unusual responses in this soil, including decreases in soil strength with disturbances and the confounding effects of soil dilation related to shearing forces, particularly those beneath vehicle tires. Trafficability, or the ability of vehicles to move across soil surfaces, long has been known to decrease in dry, sandy soils (Karafiath and Nowatzki, 1978) owing to the combined effects of lack of cohesion from low silt and clay content as well as low water contents. In addition, the presence of a vesicular A1 horizon, which is typical for soils in the North American deserts, added a complication in the initial compaction and soil disruption, as higher-than-expected changes occurred with the collapse of the large vesicular macropores. The mechanical properties of A1 horizons, particularly in soils older than the one present at the FOB site, need further study to examine the initial soil strength when dry and the reasons for decreases in soil strength with increasing applied surface pressure.

Recovery rates following disturbances like those measured at the FOB site are expected to be slow. The average recovery time for bulk density following maximum compaction in a variety of poorly sorted soils in the Mojave Desert is about a century (Webb, 2002). It is uncertain if highly compacted soils in western Arizona would respond at similar recovery rates; although minimal freeze-thaw loosening occurs in the Sonoran Desert, and wetting-and-drying cycles are more frequent owing to the summer monsoon. It is reasonable to expect that highly compacted soil, as we created in our treatments, would require at least many decades for recovery back to the undisturbed state. No studies have reported recovery rates for soil disruption in tracks.

Our results have implications for management in desert environments similar to ORPI. Poorly sorted soils are more vulnerable to compaction and are disrupted by applied surface pressure, even when at their least vulnerable dry state. As many as 10 hiker passes (50 hikers) could have minimal impact on this kind of soil, although the amount of elapsed time to the point when the trail would not be detectable is uncertain. Webb et al. (2009) found that visual recovery in heavily used motorcycle tracks required up to 20 years. As Fig. 7 shows, the rate of soil compaction is a function of applied surface pressure times the number of passes. If the applied surface pressure is reduced, by either decreasing weight or increasing the surface area of the normal stress, then the amount of impact is reduced for the same number of passes.

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